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PRE-INVESTMENT DATA
ON THE ALUMINIUM INDUSTRY

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ALUMINUM TECHNOLOGY

GENERAL

Aluminum metal is produced from alumina rich raw materials such as bauxite by a two stage process consisting of an extraction of pure alumina from the raw material followed by electrolytic reduction of the pure alumina to metallic aluminum. This electrolytic reduction process was developed simultaneously in 1886 by Hall in the United States and Héroult in France and it still remains the process on which the world's production of aluminum is based, although many improvements have of course been made in these years.

ALUMINA

Bayer process

Practically all the world's alumina production is still made by the Bayer process. A multitude of other alumina processes have been proposed and some of these are still being investigated. However, the Bayer process has proved to be a very flexible process capable of treating a wide range of bauxite qualities and also capable of producing a wide variety of alumina qualities, both with respect to chemical analysis and grain structure. From its beginning as a batch process with small units, the Bayer process has been developed into a continuous process with large units and highly efficient heat recovery systems. Trihydrate bauxite has been treated continuously for a number of years, and now the more refractory monohydrate and mixed bauxites can also be treated continuously.

The only other processes used on a commercial scale today are the Pedersen process used in Norway and in at least one plant in the Soviet Union, and a Russian process using nepheline as raw material. This latter process has already been used by the Russians for producing alumina from the Kola nepheline and it has lately been reported that a similar process will be used for producing alumina on a large scale in Siberia.

In the Bayer process finely ground bauxite is digested at elevated temperature under pressure with a caustic solution, whereby the alumina hydrate present in the bauxite is dissolved as sodium aluminate. The pressure and temperature required for the extraction depends primarily on the form in which the alumina is present in the bauxite, alumina trihydrate being more easily soluble at low temperature and pressure than alumina monohydrate. The necessary caustic is supplied as sodium hydroxide or as soda ash causticized with lime.

After completed digestion the insoluble components of the bauxite - primarily iron oxide, silica and titania - remain as a residue known as "red mud" (its colour being derived from a usually high content of

iron oxide). At the same time, a certain amount of alumina and caustic is lost in the red mud; this amount is primarily a function of the reactive silica content of the bauxite, which forms an insoluble sodium-aluminum silicate compound. The red mud is separated from the sodium aluminate solution by thickening and filtering. After filtering and washing the red mud is usually discarded by pumping the slurry to disposal areas known as "red mud lakes".

The sodium aluminate solution is cooled and pumped to precipitators where the precipitation of alumina hydrate is induced by the addition of "seed alumina", which is previously precipitated alumina hydrate. The particle size and shape of the precipitated alumina hydrate and the proportion of the alumina precipitated, are controlled by the time, temperature and agitation, as well as by the alumina and caustic concentration of the pregnant solution.

The alumina hydrate is separated and washed by thickening and filtering. The alumina hydrate is separated in wet classifiers into a coarse fraction and a fine fraction, the latter being returned to the precipitators to serve as seed alumina. The coarse alumina hydrate is calcined at 1,150 - 1,250° C in oil- or gas-fired rotary kilns. The calcined alumina is then cooled and stockpiled for shipment to the aluminum reduction plants.

The spent caustic solution from the precipitators, which still contains an appreciable amount of dissolved alumina, is returned, with makeup caustic, to the bauxite digesters. A considerable amount of water is required to wash the red mud and alumina hydrate. In order to maintain the water balance in the system it is therefore necessary to remove a corresponding amount of water by evaporation. This is usually done in multiple effect evaporators. The amount of heat required for evaporation depends on the heat exchanging efficiency of the system; considerable advances have been made in this field in recent years, resulting in fuel economies in Bayer alumina plants.

In European Bayer practice digestion temperatures of 180° to 250° C and pressures of 280 to 700 psi (20 to 50 kg/cm²) are used. Under these high temperature and pressure conditions the handling of slurries presents many technical problems and conventional monohydrate Bayer practice has therefore hitherto been based on batch operation. However, these difficulties have gradually been overcome and one must expect that continuous processing will gradually become standard also for monohydrate bauxites.

Until recently the North American industry has relied almost exclusively on trihydrate bauxites, mostly from Surinam and British Guiana. These bauxites are economically treated by the low temperature (130 to 150° C) low pressure (50 to 100 psi or 3.5 to 7 kg/cm²) Bayer process.

In recent years new bauxite sources had to be developed to satisfy the increasing bauxite requirements of the North American aluminum industry.

Thus large new bauxite deposits have been developed in the Caribbean area, particularly in Jamaica, Haiti and Puerto Rico. Some of these bauxites contain substantial amounts (up to 25 %) of monohydrate alumina besides the trihydrate and this resulted in unsatisfactory yields in conventional North American Bayer practice. Since re-treatment of the leach residue complicates the flowsheet and is usually not economically attractive it became necessary to adjust the North American continuous Bayer process to the new raw materials by increasing temperature and pressure. This has resulted in operating conditions which are a compromise between conventional North American trihydrate and European monohydrate practices.

Since 1950 the North American aluminum industry has been working on this problem. A high temperature (230°C) and pressure (400 to 560 psi or 28 to 40 kg/cm^2) continuous practice has been developed which however differs from European practice in equipment design. North American high pressure practice uses much lower caustic concentration than European practice, and this results in less solution volume to be evaporated and consequently in lower steam consumption. On the other hand, the North American high pressure technique requires a more complicated flowsheet, primarily because more flashing stages (6 to 10 as compared with 2 to 4 in conventional low pressure North American Bayer plant design) are necessary in order to achieve maximum heat economy in spite of the high temperature and pressure drop after digestion. This is to some extent balanced by more rapid digestion, also of the trihydrate part of the bauxite, at the elevated temperature and pressure. Because of its flexibility, which permits processing almost any bauxite, the high temperature and pressure practice will probably be adopted for most new alumina plants in North America.

The large trihydrate plant recently built by F.R.I.A. in Guinea, West Africa, was designed by Pechiney. It uses leaching at atmospheric pressure. This results in a considerable simplification of design and maintenance. On the other hand, the consumption of caustic and the Na_2O content of the alumina are somewhat higher because it is necessary to operate at a higher NaOH level to stabilize the sodium aluminate solution. This is however an interesting development which could result in cheaper alumina plant cost and production cost, particularly where cheap caustic is available.

Lime-soda-sinter and combination processes

When high silica (more than 10 to 15 % SiO_2) bauxites are treated by the standard Bayer process, serious alumina and caustic losses occur in the red mud, due to the formation of an insoluble sodium-aluminum silicate compound, as already mentioned. In such cases it is possible to recover a substantial proportion of these alumina and caustic values from the red mud by the lime-soda-sinter process, which was developed as an industrial process in the United States during World War II, and which is still used there for the treatment of high silica bauxites in Arkansas. In this process the red mud is mixed with limestone and soda ash, the mixture is sintered in a kiln at approximately $1,260^{\circ}\text{C}$, and the sinter is cooled, ground and leached with water. The resulting "brown

mud" is separated and discarded to waste, while the leach solution, containing sodium aluminate is returned to the Bayer plant digesters. The combination of the Bayer and lime-soda-sinter processes is generally known as the "combination process".

Acid processes

Since the infancy of the aluminum industry a large number of processes, based on extraction with acids or with solutions of strong acid salts (such as ammonium sulphate) have been proposed for recovering alumina. Such processes have particularly been suggested for the treatment of other raw materials than bauxite, which are not suitable for the Bayer process, such as various clays, alumina rich coal ashes, leucite, nepheline and andalusite, labradorite, alunite, etc.

In general, the acid processes suffer from a number of technical and economic disadvantages, such as:

- (1) Iron is soluble in acids and it is therefore difficult and expensive to fully remove iron and produce an alumina with a low iron content comparable to that obtained by the Bayer process.
- (2) Highly corrosive conditions necessitate the use of expensive construction materials, such as stainless steel, rubber lined equipment, etc. In the Bayer process common carbon steel is suitable for most of the equipment.
- (3) Some of the processes are economically dependent on byproducts such as potash.
- (4) In some acid processes the last step consists in recovering alumina from a salt, such as aluminum sulphate, by calcination. On a commercial scale this is a difficult operation and it is also difficult to produce an alumina with low sulphur content.

Efforts to produce alumina from non-bauxite raw materials by acid processes will undoubtedly continue in various quarters but it is improbable that these attempts will result in processes which are truly competitive with the Bayer process, which is a highly efficient process in its present form and which will undoubtedly be further improved in the years to come.

Pedersen process

In this process bauxite, limestone and coke are smelted together in an electric furnace. A calcium aluminate slag is formed and pig iron is recovered as a byproduct. The slag is leached with sodium carbonate solution; calcium carbonate is precipitated and a sodium aluminate solution is obtained, from which alumina hydrate is precipitated with carbon dioxide gas. The hydrate is calcined to alumina. The Pedersen

process is the only furnace process which has found commercial application; it is used in Norway, where electric power is very cheap, and a similar process is reportedly used in the Soviet Union.

ELECTROLYTIC REDUCTION

In the electrolytic reduction process, the alumina is dissolved in molten cryolite and dissociated into aluminum and oxygen. The oxygen combines with the carbon at the anode to form a mixture of carbon dioxide and carbon monoxide, whereas the aluminum is deposited at the cathode in the form of a molten metal layer underneath the cryolite.

Cryolite is a double fluoride of sodium and aluminum represented by the formula Na_3AlF_6 which melts at 1000°C . Alumina is soluble in molten cryolite and the melting temperature decreases with increasing alumina content until a minimum is reached at 935°C with 16 % Al_2O_3 . Under practical conditions the addition of alumina is limited to 5 - 10 % Al_2O_3 and the electrolytic cells operate in the temperature range 950 to 1000°C .

The gas liberated at the anode consists primarily of CO and CO_2 , as already mentioned, and the carbon monoxide burns when reaching the surface of the cryolite bath. Thus there is no hazard from carbon monoxide but the gas contains other impurities which can be objectionable particularly if the plant is located in an agricultural area. These undesirable impurities are primarily fluorine compounds resulting from the breakdown of fluorides in the cell bath, entrained cryolite and alumina dust, and tarry constituents from the anode. In modern aluminum plants the gas is therefore cleaned before being released to the atmosphere. In this way not only are valuable alumina and cryolite recovered, but the gas cleaning ensures better working conditions for the workmen and protects the vegetation of the surrounding district. The gas can be collected and cleaned by several methods, of which the more elaborate are quite expensive and only required when the plant is surrounded by valuable agricultural land.

The aluminum cells consist of an outer iron shell, lined with prebaked carbon blocks or rammed carbon paste; the iron shell is separated from the carbon lining by a layer of insulation. The cells are of rectangular shape, the size depending on the amperage used. The carbon lined shell serves as cathode and the cathodic current connection is provided by iron bars projecting into the carbon lining. The carbon lined pot also serves as container for the cryolite bath and the deposited molten aluminum.

Anode systems (prebaked and Soderberg)

The anode consists of carbon and is suspended from above into the molten cryolite bath. Two anode systems are in use, prebaked electrodes and the continuous Soderberg electrode.

The oldest system uses a number of prebaked carbon blocks in each cell. These blocks are individually suspended by iron rods hanging from the anode busbars above the cell. This system suffers from several disadvantages, such as the manufacture of the carbon blocks and the necessity of removing the blocks before they are fully used up in order to avoid contamination of the bath with iron from the suspending rods. Also, the efficient collection of the anode gas is complicated by the multitude of anodes.

The principal feature of the Soderberg system is that the anode is baked by the reaction heat from the pot as it is being continuously lowered into the bath. Green carbon paste is used as anode material and fed into the top of the anode casing. This system makes it possible to equip each cell with only one large anode. The main advantages of the system are the elimination of separate carbon forming and baking facilities, the avoidance of return materials, and the easy collection of gas along the rim of the single anode. On the other hand, the gas from Soderberg electrodes is more obnoxious because of its content of tarry components and organic fluorine compounds, and the cleaning of this gas is therefore more complicated.

In the older type of Soderberg cell, the anodic current was introduced by a number of horizontal steel studs rammed into the sides of the anode. In the more modern version of the Soderberg system, the anodic current is transmitted to the carbon paste by vertical steel studs suspended from the anode busbars and projecting into the top of the anode. The gas which is generated at the juncture of the anode and the bath, is collected in a small cast iron hood attached to the anode steel casing. In this way the amount of gas is reduced by avoiding dilution with tramp air.

All Canadian, Japanese and Soviet post-War plants are based on the Soderberg system; this has also been used in most of the new reduction plants in Europe and those built by the Reynolds Metal Company in the United States. The other main producers in the United States, such as Alcoa, Kaiser and Ormet, have preferred the prebake system. The newest reduction plant now being built by AIAG (Aluminium Industrie Aktien-Gesellschaft) in Switzerland is also based on the prebake system.

Recent developments

The main developments in recent years have been directed towards higher amperage cells and labour saving mechanization. These factors are discussed in the economic part of this report.

Although various electrolytic bath compositions have been tried out in the past, the industry still uses predominantly cryolite with small additions of aluminum fluoride and sometimes calcium fluoride. However, much research is being directed towards reducing the bath temperature and increasing the electrical conductivity of the bath by adding other salts. Of particular interest in this connection is the proposed addition of lithium fluoride, which increases considerably the conductivity and decreases the bath solidification temperature. With lithium fluoride

addition it seems possible to operate a cell at higher current density without increased anode carbon consumption, because of the lower operating temperature. Problems are the high cost of lithium compounds and their low specific gravity, which may affect cell operation.

The British Aluminium Company and Kaiser Aluminum & Chemical Corporation have for some years jointly investigated the use of refractory metal conductors, such as titanium diboride, particularly in the cathode construction. These materials have the following advantages:

- Good electrical conductivity
- High density
- High resistance to molten aluminum and cryolite

It is reasonable to expect that a substantial power reduction and a longer cathode life can be achieved with these cathode conductors. It will take considerable time to evaluate the durability of the special refractories, although the results obtained to date in full size cells in Scotland and the United States seem to be encouraging. However, the advantages would have to be quite significant to justify the high cost of these new refractory materials.

NEW PROCESSES

The idea of producing aluminum by direct reduction of aluminum compounds in electric resistance or arc furnaces is not new. However, this development has gained impetus in the last fifteen years and technically feasible solutions have been found. A semi-commercial pilot plant has been built jointly by Pechiney and Ugine for the carbothermic process in France (planned capacity: 4,000 - 6,000 tons per year) and is now in operation. Aluminium Laboratories Limited are building a large pilot plant for the subchloride process in Canada (planned capacity: 6,000 - 8,000 tons per year). Whether these processes will prove practical and economical on a large scale remains to be seen but the large capital expenditures for these pilot plants show that the aluminum companies concerned must have considerable faith in the new processes. In any case, it will take a number of years before any of these processes will become commercial and aluminum expansion will in the meantime continue to rely on electrolytic reduction.

Subchloride process

The process is based on the existence of aluminum subchloride which under certain temperature and pressure conditions decomposes into aluminum trichloride and aluminum metal according to the following reaction:



In practice, bauxite is reduced with carbon in an electric smelting furnace to an alloy of aluminum and the reduction products of the other constituents

of the bauxite, such as iron, silicon, titanium, etc. This alloy is treated at elevated temperature with aluminum trichloride gas, whereby the aluminum content of the alloy is volatilized as aluminum subchloride. The gaseous aluminum subchloride is then decomposed by altering the temperature and pressure conditions; the decomposition products are pure aluminum metal and aluminum trichloride gas, which is recycled to the volatilization or distillation step.

Carbothermic process

Bauxite is partially reduced in an electric furnace to yield a comparatively pure fused alumina (corundum) while the impurities are discarded as an alloy consisting mainly of iron, silicon and titanium with some aluminum. The fused alumina is transferred to another electric furnace where it is reduced with pure carbon to a mixture of metallic aluminum and aluminum carbide. The metal-carbide mixture is separated. The aluminum carbide is returned to the process.

FABRICATION

The most important conventional fabrication methods for aluminum are summarized in the table below:

<u>Fabrication process</u>	<u>Starting material</u>	<u>Products</u>
Flat rolling	Rolling ingots (slabs)	Sheet, plate, strip, foil
Rod rolling	Wirebars	Rod for wire and cable
Extrusion	Round ingots (billets)	Structural shapes, tubing, also rod for wire and cable (on small scale)
Forging	Extruded bar stock	Products requiring high strength, such as engine parts
Spinning and deep drawing	Circles made from rolled sheet	Hollowware, such as kitchen utensils, containers, etc.
Impact extrusion	Slugs made from rolled strip or extruded bar	Small containers
Casting (sand, permanent mould and die casting)	Molten metal	Engine blocks and pistons, and all kinds of cast shapes.

In the heavy fabrication (rolling and extrusion) the trend is towards heavier unit weights (of ingots, billets and coils), and towards higher speed machinery, as illustrated by the following figure for some of the heaviest and fastest equipment in use today:

Rolling ingot weight: up to 10 tons
Hot rolled sheet coil weight: up to 8 tons
Continuous hot sheet mill delivery speed: 1,250 feet
(380 m.) per minute
Cold sheet mill delivery speed: 3,000 feet (910 m.) per
minute
Foil mill delivery speed: 4,000 feet (1,220 m.) per
minute
Extrusion press capacity: 15,000 tons.

This trend has resulted in increasingly heavy and expensive equipment and this is particularly evident in flat rolling, which is the most important fabrication process for aluminum.

Continuous rolling mills

Prior to World War II aluminum fabrication methods, including flat rolling, followed the conventional pattern of non-ferrous metals fabrication, such as is still used for copper, brass, zinc and nickel alloys. The enormous growth of the market for aluminum sheet products in the industrially advanced countries in recent years has resulted in the adoption of equipment similar to that used for steel. Thus continuous hot rolling mills capable of reducing a 20 inch (500 mm) thick ingot directly to one-tenth inch (2.5 mm) gauge sheet in widths up to 100 inches (2.5 m) are now in operation, with production capacities ranging up to 200,000 tons per year. There are now about ten such continuous aluminum mills in the United States and two in Western Europe.

Most of the rod required for aluminum wire and cable is now produced in continuous and highly automatic rod mills where 6" x 6" (150 mm x 150 mm) wirebars are reduced to 3/8 inch (9.5 mm) diameter rod in approximately 22 passes.

New fabrication processes

The very high capital cost of the heavy equipment needed for handling large unit weights at high speeds has resulted in a keen interest in processes for the direct casting of aluminum sheet and rod.

By direct casting processes are here meant casting methods which directly produce shapes close to the final shapes desired, such as rod, strip and continuous sheet. This is pointed out to avoid misunderstanding because the expression DC casting is widely used in the United States in connection with the now generally used semi-continuous vertical casting of rolling ingots, extrusion billets and wirebars.

The production of metal shapes, such as rod, strip and sheet, having cross-sections which do not differ appreciably from those of the finished product, is now being carried out on an increasing scale. The development of a number of continuous casting processes, some of which operate in tandem with rolling mills, has shown that savings in production costs are

possible by manufacturing in this way. This is particularly true when such a continuous casting process can be tailor made for producing directly the intermediate product for mass-produced special products, such as aluminum rod for cable manufacture, narrow aluminum strip for venetian blinds and for impact extrusion slugs (for low cost production of aluminum cans), etc.

Ideas of this kind were put forward long ago but it is only since World War II that a large amount of practical work has been carried out both in Europe and North America on such processes, and that some processes have become commercially successful. A large number of methods have been proposed but only the most successful ones will be mentioned here.

In some cases, continuous casting is followed by immediate continuous hot rolling to make use of the residual heat in the cast metal. In other cases, the metal is cast in such thin cross sections that the cast product is suitable for direct cold rolling, thereby by-passing the hot rolling operation altogether. It should however be mentioned that it is not necessarily more economical to produce a thin cross-section suitable for direct cold rolling since this lowers considerably the output of the casting machine; on the other hand, a direct cast say 1 inch (25 mm) thick slab can be immediately hot rolled (using the remanent heat present in the slab) in a simple and cheap hot rolling mill, thus taking advantage of the higher output of the casting machine producing such a comparatively thick slab.

The most successful direct casting processes to date are the following:

Wheel-and-belt type casting machines

In these machines the liquid metal is poured into a groove on the outer edge of a wheel, and the groove is closed by a steel strip. Cooling is applied as the wheel and the strip turn around, and the cast shape emerges after solidification of the metal.

The propersi machine, developed in Italy, has found wide use all over the world for the casting of a triangular shaped bar which is directly converted into 3/8 inch (9.5 mm) diameter rod by continuous rolling on a special tandem mill installed next to the casting machine.

The Rigamonti and Coors machines use the same principle for the manufacture of strip for impact extrusion of cans.

Twin-belt type casting machines

In this type of machine the molten metal is fed between two moving steel belts, which are water cooled on the back side. The solidified aluminum strip or sheet emerges from the other end of the parallel travel length of the belts.

Two machines of this type are in successful commercial operation today: the Hunter-Douglas machine which produces a narrow slab for the continuous production of venetian blinds, and the Hazelett machine which produces an approximately 1 inch (25 mm) thick slab in widths up to 40 inches (1 m). The Hazelett slab can be directly hot rolled in a comparatively cheap hot mill. The Hazelett machine has been installed during the last few years in the United States and Canada.

Twin-roll type casting machines

Actually the idea of casting metal continuously between two chilled rolls is very old but it is only in recent years that a practical method, based on this principle, has been developed by the Hunter Engineering Company in the United States. In the Hunter machine the molten metal is fed from underneath through a distributor between two revolving water-cooled cylinders. The cast strip, approximately $\frac{1}{4}$ inch (6 mm) thick, emerges vertically upwards between the cylinders and is coiled as-cast, for further reduction by cold rolling. Hunter machines are now installed in several aluminum mills in the United States and Australia. To date the greatest cast width is approximately 60 inches (1.5 m).

Oscillating-mould machines

It has long been known that shapes can be cast at greater speed when the mould follows the shape for a limited distance and then jumps back to its starting position, and so on. These so-called oscillating mould processes have been used for a number of years for the casting of large rolling ingots, etc., but it is only quite recently that a horizontal oscillating-mould casting machine was developed by Tessmann for the production of thin bar suitable for direct rolling to rod. Several of these machines are now in operation in the United States.

It is reasonable to expect a continued trend towards the use of direct casting processes, particularly by small and medium sized fabricators where the quantities of metal required do not justify the installation of major fabricating facilities. These processes should therefore be of considerable interest to underdeveloped countries wishing to establish an aluminum fabricating industry on a moderate scale.

RAW MATERIALS

Bauxite is the richest and most easily treated aluminum raw material. Aluminum is also present in a number of common minerals but there is little economic incentive to use these in view of the abundant reserves of bauxite which exist in many parts of the World.

The aluminum industry also requires a variety of auxiliary raw materials. The most important of these are: pure carbon (usually in the form of petrol coke or pitch coke), cryolite and caustic (in the form of caustic soda or soda ash and lime).

BAUXITE

Aluminum is the metal which occurs in the largest quantity in the earth's crust and it is an important component of practically all common rocks. The aluminum silicates present in primary rocks have been broken down by weathering processes whereby the alumina has become enriched in clays and bauxite.

Under normal economic conditions the only commercial raw material for aluminum production is bauxite. Bauxite is basically hydrated aluminum oxide, with varying contents of impurities. The degree of hydration and the nature and quantity of the impurities are all important economic factors in the processing of bauxite to pure alumina.

Alumina monohydrate $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ occurs in two mineralogically different forms, boehmite and diaspore. Of these, boehmite is soluble in caustic solutions, but much higher temperature and pressure are required than for gibbsite, the typical trihydrate bauxite mineral. Diaspore, on the other hand, is very refractory to caustic leaching.

Consequently, the Bayer process is applicable to monohydrate bauxites in which boehmite is the main constituent. Most bauxites mined in Europe are of this type and Bayer process practice for monohydrate bauxites is therefore primarily a European development. Monohydrate bauxites with high diaspore content are mined in Greece and in the Soviet Union. These bauxites are not suitable for the Bayer process and an important proportion of the Greek bauxite production therefore goes to Norwegian and Soviet alumina plants using a modified Pedersen process.

Alumina trihydrate $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$, in the form of the mineral gibbsite, is the main constituent of most bauxites found in West Africa, British Guiana, Surinam, West Australia, Malaya, Indonesia and the United States. These bauxites are the cheapest to treat by the Bayer process practice for trihydrate bauxites developed in North America, and this type of bauxite is therefore the most desirable. Until recently, only trihydrate bauxite was used for alumina production in Canada, the United States and Japan.

In recent years mixed bauxites, in which the alumina is present partly as monohydrate and partly as trihydrate, have grown in importance

as raw materials for the aluminum industry. Thus the large bauxite deposits which have been developed in the Caribbean area, particularly in Jamaica, Haiti and Puerto Rico, are to a considerable extent mixed bauxites with 1 to 25 % monohydrate. Most bauxites found in India and North Australia are also mixed, with trihydrate as the predominant constituent. To successfully treat these mixed bauxites it has been necessary to adjust the conventional trihydrate Bayer process as the presence of even a small amount of monohydrate alters the digestion conditions.

Effect of impurities

The most objectionable impurity is silica. Silica occurs in bauxite in two forms:

- (1) reactive silica, which is chemically combined as clay or other silicates
- (2) non-reactive silica, such as quartz, sand, chalcedony, etc.

The reactive silica causes losses of alumina and caustic in the red mud, as already mentioned. The losses are of the following order:

$$\begin{aligned}\text{alumina loss} &= 1.0 \times \text{reactive silica} \\ \text{caustic loss (as NaOH)} &= 0.9 \times \text{reactive silica} \\ \text{caustic loss (as Na}_2\text{CO}_3) &= 1.2 \times \text{reactive silica}\end{aligned}$$

Only the reactive silica causes losses of alumina and caustic when digesting trihydrate bauxites at low temperature and pressure, as quartz is not attacked under those conditions. When monohydrate bauxites are digested at high temperature and pressure, however, silica in all forms is attacked and the total silica content of the bauxite results in losses of the order shown above; in these bauxites the total silica content can therefore be considered as "reactive".

Iron oxide is normally not harmful except in so far as it increases the bulk of the red mud thus causing additional washing and handling problems when present in large amounts. Bauxites with up to 25 - 30 % Fe_2O_3 are successfully treated by the Bayer process. In certain bauxites some of the alumina seems to be combined with insoluble hydrated iron oxide minerals and in these cases the iron oxide does cause an alumina loss.

Titania is not soluble and therefore generally harmless in the Bayer process. In India bauxites with up to 11 % TiO_2 are successfully treated by the Bayer process.

Other minor impurities, such as vanadium and phosphorus, can also cause problems.

Evaluation of bauxite quality

The most important factors governing the economic value of a bauxite are as follows:

(1) Hardness

Determines the cost of grinding the bauxite. Bauxites range all the way from earthy materials (Jamaica) to hard rock (Greece and India). Bauxites with Bond hardness index above 15 are expensive to grind.

(2) Extractable alumina

The proportion of alumina which is theoretically extractable by the Bayer process can be approximately estimated by the following formula:

$$\% \text{ extractable Al}_2\text{O}_3 = 100 \% - 2 \times \% \text{ SiO}_2 - \% \text{ Fe}_2\text{O}_3 - \% \text{ TiO}_2 - \% \text{ H}_2\text{O}$$

If the low temperature and pressure Bayer practice is to be used for a trihydrate bauxite, the % monohydrate Al_2O_3 must also be subtracted.

However, while the above formula will give a rough indication, to determine more accurately the available Al_2O_3 it is necessary to carry out laboratory digestion tests using standard temperatures, pressures and digestion times. The amount of alumina which is extractable under industrial conditions is actually somewhat less, because of unavoidable losses due to incomplete washing of red mud, etc.

(3) Caustic losses, red mud characteristics, etc.

It is usual to follow up the above tests with further digestion tests simulating the proposed Bayer practice. Practical values for extractable alumina, caustic losses, mud quantities, and mud settling and filtration characteristics, all of which are important for the economics of processing the bauxite, are obtained from this test work.

(4) Moisture content

This is the "free moisture" content, i.e. the water present in addition to chemically combined water. This affects the drying cost, which is important if the bauxite is to be shipped somewhere else for processing. When bauxite is processed in an alumina plant at the mine site, it is often not necessary to dry it.

Mining methods

Practically all bauxite produced in the Western Hemisphere, Africa and Australia is mined by open-pit methods. In Europe some bauxite is produced by underground mining but also there most of the production comes from open-pit operations.

Open-pit mining of bauxite consists usually of the following operations, when mining is carried out on a comparatively large scale:

(1) Removal of overburden

Up to 150 feet (50 m) thick overburden is removed in certain bauxite mining operations today. No definite figures can be given for the maximum amount of overburden which can be economically removed as this obviously depends on a number of factors such as the nature of the overburden, the quality of the bauxite, and the size and location of the mining operation. In the case of large scale operations and high grade bauxite, the economic limit is usually 5 to 8 times the amount of bauxite recovered.

Sandy and earthy overburden is usually removed with bulldozers, bucket excavators, draglines, by hydraulic mining, and, most recently, by large wheel excavators. The latter have capacities of up to 1,200 tons per hour.

(2) Removal of bauxite

Similar methods are used for removing the bauxite itself. Usually the bauxite must first be loosened by blasting.

(3) Replacing of overburden

In some countries it is desirable to recover the surface over the deposit for re-use as forest or agricultural land. The overburden is then continuously stripped ahead of the advancing bauxite mining operation and dumped behind it. Draglines or belt conveyors take the overburden directly from the stripping zone to the replacement zone. This mode of operation is economical for large bauxite mining operations under heavy overburden, even when re-establishment of the former surface is not important.

Economic factors in bauxite mining

The main factors determining the economy of a bauxite mining operation are as follows:

(1) Quality of bauxite

The factors determining bauxite quality have already been discussed. Typical analyses of bauxites mined in various parts of the world are shown in a table attached to this report.

(2) Size of deposit and mining operation

Bauxite is a cheap commodity which occurs in large deposits in many places. The following countries have the largest known ore reserves:

Between 50 and 100 million tons:	Surinam, British Guiana, France, Greece, Soviet Union, United States
----------------------------------	--

Between 100 and 1,000 million tons: Jamaica, Ghana, Guinea, Hungary, Yugoslavia, possibly Brazil

More than 1,000 million tons: Australia.

The largest individual mining operations, each of the order of 1 to 2 million tons of bauxite per year, are carried out in Surinam, British Guiana and Guinea. In Jamaica there are several mining operations of this order of magnitude. The opening up of such large mining operations requires investments, running into many millions of dollars, for the necessary mechanical equipment and for preparing large surfaces for mining.

(3) Amount and nature of overburden

This is a very important factor as the amount of overburden often greatly exceeds the amount of bauxite found below it. Dry, sandy overburden is cheaper to remove than wet, earthy overburden covered by dense jungle.

(4) Location

Transportation costs are very important for such a cheap commodity as bauxite. Consequently, the accessibility of a bauxite deposit is of prime economic importance. It should preferably be located close to tidewater (sea coast or navigable river), such as the deposits in Jamaica, Greece, Surinam, British Guiana and Australia. In Europe, where distances are comparatively small, bauxite is shipped by railways from mines in Southern France, Hungary and Yugoslavia. The economic exploitation of deposits located far inland usually requires local processing of the bauxite in alumina plants close to the mine site, such as in Arkansas (United States) and Guinea; this is particularly true when the bauxite is of low grade.

Beneficiation of bauxite

In the commercial beneficiation of bauxite the main purpose is usually to remove silica. Reactive silica in the form of clay and other loose impurities is removed by washing and classification. This is however not always possible as in some cases the alumina hydrate is almost as fine and soft as the clay minerals.

Raw bauxite from the mines is usually crushed, washed and dried to lower the tonnage to be shipped. Drying is carried out in rotating kilns at moderate temperature to remove the free moisture without removing the water of hydration. Natural gas or heavy oil is preferably used as fuel rather than coal, to avoid contamination with ash. The largest drying kilns in operation handle about 70 tons of bauxite per hour. Fuel consumption varies considerably as it depends on the moisture

in the bauxite and the design and size of the drying kiln; 6 US gallons or 23 litres of heavy fuel oil per ton of bauxite is probably an average figure.

Price and production cost of bauxite

The price of bauxite depends of course on its quality. Long term contracts for large tonnages are always negotiated at prices lower than those shown in official quotations.

High grade trihydrate bauxite from Surinam and British Guiana is sold to independent purchasers for US \$ 6.50 - 7.00 per long ton f.o.b. port of shipment, basis:

53 % extractable Al_2O_3 (note: total Al_2O_3 is approximately 6 % higher)
4.5 % reactive SiO_2
dried to 2.5 % moisture.

Premiums are paid for additional extractable alumina and for less reactive silica. Thus the f.o.b. price of Jamaica bauxite, with considerably lower extractable alumina content, is only of the order of US \$ 4.50 - 5.50 per ton.

Actual production costs are lower and the major US aluminum producers land bauxite from their own mining operations in South America and the Caribbean islands at their alumina plant on the Mexican Gulf coast at costs in the order of US \$ 7.00 to 8.00 per ton; this cost includes:

	<u>US \$</u>
Mining, inclusive amortization of equipment, exploration etc.	1.00 - 3.00
Beneficiation	nil - 1.00
Drying	0.75 - 1.50
Shipping	3.00 - 4.50
Local taxes, mining and (in some cases) shipping company profits	balance

The major North American aluminum companies (Alcoa, Kaiser, Reynolds and Alcan) control the main bauxite mining operations in this area. Alcoa and Alcan also have subsidiary shipping companies which operate cargo ships carrying the bauxite from South America and Jamaica to their alumina plants. Consequently, the cost of bauxite to these companies includes profits made by their mining companies and in some cases by their shipping companies; such profits should of course be subtracted to arrive at the true cost of the delivered bauxite. On the other hand, the mining companies pay royalties and taxes to the countries in which they operate.

The price of French monohydrate bauxite in September 1962 was NF 17.68 (US \$ 3.60) per metric ton f.o.b. mine in Southern France, basis:

54/55 % Al_2O_3
5 % SiO_2

Premiums for better grades amount to NF 0.68 (US \$ 0.14) for each percent Al_2O_3 above 55 % and NF 2.04 (US \$ 0.41) for each percent SiO_2 below 5 %.

The price for average grade delivered by French bauxite mines is about NF 21.00 (US \$ 4.25) f.o.b. mine.

Exploration, mining, beneficiation, drying and transportation costs for bauxite vary very considerably from one location to another, and this also applies to the investment required in each individual case. Bauxite production costs cannot be related to the scale of mining because so many other factors, which depend on geographic conditions, enter the picture. The costs of a new bauxite mining operation must be estimated and assessed against the bauxite costs and prices shown above for some of the leading bauxite mining countries.

In general it can be said that bauxite is such a cheap commodity and occurs in such large deposits in many parts of the world that it is usually not economical to mine small deposits without efficient mechanical equipment. Most bauxite mining operations in tropical under-developed countries are on a scale of at least 300,000 tons per year and highly mechanized; this scale is usually needed to achieve an economic mining operation in a remote location where all facilities, such as electric power, transportation facilities, townsite etc., have to be provided and amortized by the mining operation. In locations where such facilities are readily available, mining can be economically carried out on a smaller scale; thus bauxite mining is often on a much smaller scale in Europe where transport facilities, power supply and existing habitations are usually close at hand.

However, it is under certain circumstances economical to mine bauxite on a smaller scale, say from 50,000 tons per year and up, also in industrially less developed countries. Such conditions exist when there is little overburden and the bauxite is of high grade. But the best conditions for such small scale mining exist when it can be integrated with alumina production at or close to the mine site; this has been done in Brazil and India.

OTHER ALUMINOUS RAW MATERIALS

Aluminum is more widely distributed in rocks and clays than any other metal and consequently there exists many minerals which appear to have an attractive content of alumina. In course of the last half-century many other minerals have therefore been proposed for processing to alumina. These alternative raw materials include aluminous clays such as kaoline, alumina rich coal ashes, leucite, nepheline, andalusite, labradorite and alunite.

Bauxite is however the only economical raw material for alumina production under competitive conditions. Other raw materials have been used in wartime and in countries following a policy of self-sufficiency. Thus andalusite was used in Sweden and aluminous clays in Germany and the United States on a trial basis during World War II. Nepheline is used in the Soviet Union where good grade bauxite is not available. Leucite

was used for some time in Italy. All these countries have however reverted to bauxite, with the exception of the Soviet Union which has poor bauxite reserves and follows a policy of self-sufficiency. It follows from this that a competitive alumina production in most countries would have to be based on imported bauxite if no domestic bauxite is available, even if deposits of other aluminous minerals exist in the country.

The only non-bauxite raw material which is used today on a large scale is nepheline, a sodium-potassium-aluminum silicate with approximately 34 % Al_2O_3 . This is obtained as a byproduct from the beneficiation of apatite mined on a large scale on the Kola Peninsula. This nepheline is used for the production of alumina in the Soviet Union, whereby potash is obtained as a byproduct. The process is therefore similar to the Kalunite process developed on a semi-commercial scale in the United States during World War II. It has lately been reported that a similar process will be used for producing alumina on a large scale in Siberia.

FLUORIDES

Fluorides, in particular cryolite (sodium-aluminum fluoride) and aluminum fluoride, are important auxiliary raw materials in aluminum production by the electrolytic reduction process.

Natural cryolite occurs only in Greenland in commercial quantities. This cryolite is refined in Denmark. Natural cryolite is not available in sufficient quantity for the growing requirements of the aluminum industry and a considerable proportion of the cryolite used today is synthetic. The synthetic cryolite is usually made from fluorspar, sulphuric acid and sodium aluminate solution. The present price of cryolite is approximately as follows:

United States:	approx. US \$ 285 per short ton (natural)
France:	NF 1,500 (US \$ 300) per metric ton (synthetic)

Aluminum fluoride is always produced synthetically from fluorspar, sulphuric acid and alumina hydrate. The price in the United States is approximately US \$ 360 per short ton.

From this it will be understood that fluorspar is now indirectly the basic raw material for the fluorides used by the aluminum industry.

ELECTRODE MATERIALS

In the electrolytic reduction process electrode materials are mainly used in the anodes but also in the cathodes which have to be replaced from time to time.

The main raw materials are:

- (1) a pure form of carbon, such as petrol or pitch coke
- (2) a pure carbonaceous binder, such as pitch.

Of these, pure coke is economically the most important. Petrol coke is obtained as a product of petroleum refining. Pitch coke and pitch are byproducts of coal coking plants.

CAUSTIC

Caustic is required for the Bayer alumina process. The quantity needed depends on the quality of the bauxite and varies within wide limits (from 30 to 120 kg per metric ton of alumina).

Caustic is used in the form of sodium hydroxide or soda ash (sodium carbonate). When using soda ash an equivalent amount of burnt and slaked lime is required for causticizing.

FUELS

Fuels are particularly used for the drying of bauxite and in the alumina process for steam generation and for calcination of alumina. Any suitable boiler fuel can of course be used for steam generation. Oil or gas should preferably be used for the drying of bauxite, as fly ash from coal increases the undesirable impurities, in particular silica, in the dried bauxite. In the case of alumina calcination it is imperative to use oil or gas, for the same reason.

ALUMINA

The following data refer to the Bayer process which is almost universally used for alumina production today. Furthermore, these data are based on treating a typical trihydrate bauxite from Surinam or British Guiana (extensively used for alumina production in North America), and a typical monohydrate bauxite from Southern France (extensively used in Europe), of the following approximate compositions:

	<u>Trihydrate bauxite</u>	<u>Monohydrate bauxite</u>
Al ₂ O ₃	57 %	53 %
SiO ₂	4 %	6 %
Fe ₂ O ₃	5.5 %	25.5 %
TiO ₂	1.5 %	3 %
N ₂ O	32 %	12.5 %

It must be emphasized that the capital cost and operating requirements vary considerably with the source and composition of the bauxite treated.

CAPITAL COST

Typical order-of-magnitude investment figures for alumina plants today are shown below. Ranges are shown, in view of the many variables.

<u>Plant capacity</u>	<u>US \$ per metric ton annual Al₂O₃ capacity</u>	
<u>Metric tons per year</u>	<u>Trihydrate bauxite</u>	<u>Monohydrate bauxite</u>
100,000	170 - 210	190 - 230
165,000	140 - 180	160 - 200
330,000	110 - 150	140 - 180

The graph shows average investment per annual ton alumina capacity for trihydrate and monohydrate plants with capacities ranging from 100,000 to 330,000 tons of alumina per year (300 to 1000 tons per operating day).

The capital cost figures include the complete plant but not outside facilities which depend completely on local conditions. The following defines the figures shown:

Included

- Equipment
- Buildings
- Foundations
- Steam plant
- Direct plant services, such as:
 - power and steam distribution within plant area
 - materials handling within plant area
 - plant office

laboratory
change house
maintenance workshops
Storage and handling facilities for:
bauxite
fuel oil
alumina
operating and maintenance supplies

Excluded

Bauxite mining, beneficiation and drying plant
Townsite (dwellings, schools, hospital, community facilities, etc.)
Power generation and transmission to plant site
Wharf, railway, roads, etc. (i.e. transport facilities outside of plant area)
Caustic soda or soda ash production facilities
Limestone mining, crushing, and burning facilities.

The capital cost is considerably increased if a lime-soda-sinter plant or other additional process facilities are included. This may be necessary in order to obtain a satisfactory alumina recovery and to limit caustic consumption, if bauxite with high silica content (say above 7 % SiO_2) is to be treated.

The following figures are typical of good operating practice today in modern large (say 1,000 tons alumina per day) plants. The figures below show quantities per metric ton of calcined alumina, and are given on the same basis as the capital cost figures above.

	<u>Trihydrate bauxite</u>	<u>Monohydrate bauxite</u>
Bauxite, tons	2.1	2.5
Caustic, as kg NaOH	80	140
Steam, tons	2.0	2.4
Electric power, KWH	200	275
Fuel for calcination (shown as litres of fuel oil)	130	130
Labour (operating, maintenance and indirect), manhours	3	4
Maintenance (materials and equipment), US \$	3.00	4.00

Some of these requirements are influenced considerably by various factors, as explained below.

Amount of bauxite required

The amount of bauxite depends on the bauxite quality and can be figured out from the extractable alumina content. In addition, a reasonable

allowance should be made for miscellaneous plant losses (3 to 4 %).

Caustic consumption

The caustic consumption varies over a wide range, depending primarily on the reactive silica content of the bauxite, and to a smaller extent on the amount of residue washing. The amount required for a given bauxite analysis will in practice be slightly higher than the figure which can be calculated from the formulas already shown in the section "Raw Materials":

$$\begin{aligned}\text{caustic loss (as NaOH)} &= 0.9 \times \text{reactive silica} \\ \text{caustic loss (as Na}_2\text{CO}_3) &= 1.2 \times \text{reactive silica}\end{aligned}$$

and from the amount of bauxite needed (see above). To the calculated figure should be added a small allowance for washing losses. This allowance depends on the amount and filtering characteristics of the red mud formed.

Steam consumption

This is primarily a function of heat exchanger efficiency. If fuel is expensive it pays to spend more capital on heat exchanger capacity. Steam consumption also decreases with increasing plant size and with improved bauxite quality. Steam consumption is higher for monohydrate than for trihydrate bauxite, due to the higher digestion temperature and pressure.

Steam consumption (tons steam per ton alumina) therefore varies within a wide range, as shown below:

Trihydrate bauxite:	1.5 to 4
Monohydrate bauxite;	2.2 to 7

The lowest figures are for large plants (1000 tons Al_2O_3 per day), high grade bauxite and high efficiency heat exchanger systems. The highest figures are for small plants (150 tons Al_2O_3 per day), low grade bauxite and poor heat exchanger efficiency.

In many cases steam production is combined with electric power generation and this of course affects the overall steam consumption. Power generation is economically attractive in isolated locations where electric power is not available from an established grid system, and also often in connection with monohydrate bauxite treatment because of the high available steam pressure.

Electric power

Power consumption increases somewhat with decreasing plant size. Small plants may require:

Trihydrate bauxite:	up to 300 KWH per ton
Monohydrate bauxite:	up to 420 KWH per ton

Power consumption also depends on the hardness of the bauxite used, as considerable energy is required to grind hard bauxites prior to digestion.

Fuel for calcination

Calcination fuel does not vary with plant size provided large modern kilns are used (capacity per kiln: 250 to 500 tons alumina per day).

Labour

Labour requirements per ton alumina vary of course with plant size but depend also on many other factors.

Thus maintenance and indirect (yard gang, truck drivers, watchmen etc.) labour requirements are reduced if the alumina plant is integrated with a bauxite mining operation or an aluminum reduction plant. Under such conditions it is possible to get down to 2 to 3 manhours per ton alumina.

On the other hand, a self-contained alumina plant (with its own complete maintenance facilities) in an isolated location in tropical climate usually requires considerably more labour, even if the plant is of modern design. Under such circumstances it is prudent to figure with 5 to 8 manhours for a good size plant (500 to 1000 Al_2O_3 per day), and even more for a smaller plant.

Maintenance

This item varies with plant size, location, integration with other operations (mining or reduction), and with the skill and experience of the labour and supervisory staff. Under favourable conditions this cost item can be reduced to US \$ 2.00 to 3.00 per ton Al_2O_3 , whereas it can increase to US \$ 5.00 or even more under particularly unfavourable conditions.

SOURCES OF CAUSTIC

Caustic can be supplied to the Bayer process either as caustic soda or as soda ash in combination with burnt lime, as already mentioned.

In cases where caustic is expensive and electric power comparatively cheap, it may be justified to install an electrolytic caustic-chlorine plant locally. The raw material is sodium chloride (common salt) which can be obtained at low cost in many locations. The economy of the caustic-chlorine plant depends however on a market being available for the chlorine; such a market exists in countries with a well developed chemical or petrochemical industry but is often non-existent in industrially under-developed countries.

In certain cases it may be more attractive to build a soda ash plant, which can use ammonia from a fertilizer plant. The minimum economic

size of a Solvay (ammonia) process soda ash plant is however considerably larger than that of an electrolytic caustic-chlorine plant.

No definite figure can be given for the maximum price that can be paid for caustic to be used in alumina production. The consumption of caustic varies greatly with bauxite quality, as already pointed out; for this and other reasons, the maximum economic cost of caustic must be determined for each individual case.

MINIMUM ECONOMIC SIZE OF PLANT

Economic circumstances vary so much that the minimum plant size must of course be determined in each individual case. However, the following sizes are given as an indication, in tons Al_2O_3 per year production capacity:

- (1) Self-contained alumina plant:

North America	100,000 - 165,000
Europe	50,000 - 60,000
- (2) Alumina plant connected with mining of a bauxite deposit in an underdeveloped country, based on export of alumina to world markets: 100,000 - 165,000
- (3) Alumina plant in underdeveloped country, combined with reduction plant for local aluminum market: 30,000 - 40,000

In this connection it should be pointed out that the economy improves with increasing capacity up to 330,000 tons Al_2O_3 per year (1000 tons per operating day) which is about the largest practical unit size. A larger plant will therefore consist of two or more parallel production units; cost savings then become less marked but some savings are of course still possible for such items as plant administration and maintenance.

ALUMINUM REDUCTION

The following data refer to the electrolytic reduction process which is universally used for aluminum production today. Two types of reduction plants, based on the prebaked and Soderberg anode systems, are widely used today and data are shown for both.

CAPITAL COST

Typical order-of-magnitude investment figures for aluminum reduction plants today are shown below. Ranges are shown, in view of the many variables:

<u>Plant capacity</u> <u>Metric tons per year</u>	<u>US \$ per metric ton annual Al capacity</u>	
	<u>Prebake plant</u>	<u>Soderberg plant</u>
20,000	1000 - 1300	900 - 1200
50,000	750 - 1050	700 - 1000
100,000	650 - 850	650 - 850
200,000	500 - 700	550 - 750

The graph shows average investment per annual ton aluminum capacity for prebake and Soderberg reduction plants with capacities ranging from 20,000 to 200,000 tons of aluminum per year.

The capital cost figures include the complete plant but not outside facilities which depend completely on local conditions. The following defines the figures shown:

Included

- Power supply and distribution, including:
 - substation with transformers
 - rectifiers
 - DC busbar system
 - AC power distribution within plant area.
- Aluminum reduction plant (potrooms)
- Carbon plant (prebaked anodes or Soderberg paste plant)
- Cast house (for refining, alloying and casting produced metal into ingots and shapes for shipping)
- Gas removal and cleaning facilities
- Direct plant services, such as:
 - materials handling within plant area
 - plant office
 - laboratory
 - change house
 - maintenance workshops
- Storage and handling facilities for:
 - alumina
 - fluorides
 - carbon plant raw materials
 - aluminum ingots and shapes
 - operating and maintenance supplies

Buildings and foundations for all above items.

Excluded

Power generation and transmission to plant site
Townsite (dwellings, schools, hospital, community facilities, etc.)
Wharf, railway, roads etc. (i.e. transport facilities outside of plant area)
Synthetic cryolite and aluminum fluoride production and regeneration facilities

Factors influencing capital cost

The effects of the anode system (prebake versus Soderberg) cell size and power cost are discussed under separate headings in this section of the report.

In a reduction plant the electrolytic cells are arranged in series, known as pot lines, the anode of one cell being connected to the cathode of the next cell, and so on. Each potline forms a loop with the positive and negative ends connected with the rectifier group feeding the potline with direct current. The maximum rectifier voltage is 350 volts and the average voltage per cell is about 5 volts, when including all voltage drops in the system. In practice this means that a maximum number of about 160 cells, with an average of 150 cells in operation, can be accommodated in one potline. The maximum annual production of such a potline is shown here for cells of various amperages (assuming 87 % current efficiency):

<u>Direct current</u> <u>in amperes</u>	<u>Metric tons Al</u> <u>per cell per day</u>	<u>Metric tons Al</u> <u>per year (150 cells)</u>
40,000	0.28	15,000
60,000	0.42	22,500
80,000	0.56	30,000
100,000	0.70	37,500
120,000	0.84	45,000

The lowest capital cost per ton aluminum capacity is achieved by building one or several complete potlines, i.e. with the maximum number of cells for the chosen amperage. In this way the maximum number of production units (cells) are serviced by the same rectifier group, cranes, etc.

Capital cost is also to some extent influenced by climate. In cold and temperate climates it is customary to install two parallel rows of cells arranged end-to-end, or a single row of cells arranged side-to-side, in each potroom building; these arrangements normally provide sufficient ventilation to ensure adequate working conditions in the potrooms. In a tropical climate, however, it is advisable to install only one line of cells arranged end-to-end in each potroom building, particularly if high amperage cells are chosen. This increases the building area, the number

of cranes, etc., resulting in a higher capital cost.

The anode gas from the cells and the potroom air contain dust (alumina, fluorides and carbon particles) and, in the case of a Soderberg plant, also tarry fumes. Both the anode gas and the potroom air can be more or less cleaned before being released to the atmosphere, depending on the surroundings. Elaborate gas and potroom air cleaning installations may be required if the plant is located in an agricultural district or close to a town, or if dictated by prevailing winds and topography. This can cause a substantial increase in capital cost.

Capital cost for an identical plant varies from one part of the world to another. Thus the capital cost for the same plant (same design and same size) is lower in Western Europe than in North America. However, average investment per annual ton aluminum capacity is probably higher in Europe because of smaller plant size and more elaborate gas cleaning and power saving designs. Comparatively high capital cost must be expected in under-developed countries due to distance from equipment sources and because very complete maintenance facilities are required. Aluminum reduction plants mostly use heavy and rugged equipment, due to high unit weights of materials to be handled; consequently, the possibilities of replacing mechanization with manual labour, and thereby save on capital cost, are limited. The experience is that hard and hot work, such as crustbreaking, metal tapping and anode and pin changing in the potrooms, is more reliably and efficiently carried out with machines than with hand labour, particularly in tropical climates.

Cost of expanding existing plants

The cost of expanding existing plants is usually considerably less, per annual ton aluminum capacity, than that of new plants. It is particularly cheap to add new electrolytic cells to a potline where the voltage capacity of the rectifiers has not yet been fully utilized. But it is also economical to add new potlines to existing reduction plants; thus a new 23,000 tons per year potline, including auxiliary installations such as rectifiers, carbon plant, cast house, gas cleaning and maintenance workshops extensions, was recently added to an existing European plant at a cost of about US \$ 550 per annual ton. In general the cost of additional potlines is from two-thirds to three-quarters of the cost of a new plant, and the addition of new cells to an existing potline provides capacity at even lower cost.

OPERATING REQUIREMENTS (CONSUMPTION FIGURES)

The following figures are typical of good operating practice today in modern (well mechanized) plants of medium capacity (say 60,000 tons per year). The figures below show quantities per metric ton aluminum for prebake and Soderberg plants, using cells of similar size (about

80,000 amperes):

	<u>Prebake</u>	<u>Soderberg</u>
Electric power, KWH	17,000	17,500
Alumina, tons	2	2
Fluorides, kg as F	2.5	3.5
Anode carbon (net), kg	500(1)	560(2)
Total labour:		
Total plant(3)	18	15
Potrooms only	8	7
Operating and maintenance		
Supplies, \$(4)	20	18
Remarks:		
(1) prebaked carbon anodes		
(2) Soderberg paste		
(3) includes carbon plant maintenance, supervision and indirect labour		
(4) includes cathode replacement		

Some of these requirements are influenced considerably by various factors, as explained below.

Electric power

The power consumption depends mainly on the following factors:

Cell design

Power consumption can be lowered by decreasing current density, using low resistance cathode constructions and other design changes. All these measures increase the capital cost, however, and the extent to which such technical improvements are economically justified, depends on the availability and cost of power.

Busbar design

Power consumption can be decreased by increasing the busbar cross-sections to lower busbar resistance. The undesirable effects of electromagnetic fields can be countered with more complicated busbar layout. In both cases the result is more aluminum and, in some cases, copper invested in busbars. Also in this case the availability and cost of power determines whether such technical improvements are economically justified.

Good operating practice

This is of course most important. Accurate supervision and control as well as well trained and efficient labour is required to obtain the best results. Even with an experienced crew it may

take considerable time to achieve good results with a type of cell with which they are not accustomed; this is particularly true of the large (high amperage) cells which have been introduced in recent years.

The power consumption figures shown above refer to total power consumed by the reduction plant with all its auxiliary installations, i.e. power delivered to high voltage intake. Besides the DC power consumed in the electrolytic cells, these figures include:

- (1) Mechanical power (cranes, conveyors, compressed air and vacuum systems, etc.),
- (2) Gas removal and purification system. This requires considerable power if purification of both the cell gas and potroom air is necessary.
- (3) Transformer and rectifier losses.

This is pointed out because much lower power consumption figures are sometimes published. Such figures refer to the net DC power consumed in the electrolytic cells. The lowest DC power consumption figures, 14,000 to 15,500 KWH, are obtained in the most recent reduction plants in France and Switzerland; however, these low figures are obtained by using expensive cell and busbar designs. In countries with cheap power such as Canada and Norway, it is more economical to use cheaper cell and busbar designs and the power consumption is correspondingly higher, from 16,500 to 18,500 KWH in modern plants. In the United States the power consumption is between the above figures.

Alumina

Alumina consumption is constant. Good housekeeping must, of course, be enforced to avoid spillage losses when handling the alumina. Floor sweepings are always reused in cells producing lower purity metal.

Fluorides

Fluoride consumption depends primarily on operating practice. Fluoride consumption increases with cell operating temperature and with the acidity (i.e. AlF_3 : NaF ratio) of the electrolyte bath. However, it may still be advantageous to operate with an acid bath because of better current efficiency.

Fluorides are mostly lost in the anode gas and in the cathodes. Fluorides are expensive and are therefore in some plants recovered from the gases and from used cathode linings.

Anode carbon

The anode carbon consumption depends on:

- (1) The quality of the raw materials (petrol coke, pitch coke and pitch)

(2) Careful manufacture of the carbon paste and prebaked carbon anodes.

(3) Potroom operating practice.

Poor carbon paste quality and poor cell operation result in considerable carbon losses from burning of the anode sides, and disintegration of the anode.

The lowest carbon consumption figures obtained today are approximately as follows:

Prebake carbon anodes:	450 - 480 kg
Soderberg anode paste:	520 - 530 kg

However, the consumption is considerably higher in many plants, often in the 600 to 700 kg range. A close co-operation between the potrooms and the carbon plant assists in obtaining the best results and it is therefore an advantage for a reduction plant to have its own carbon plant rather than purchase anode carbon from outside.

The following figures show the order-of-magnitude of anode carbon costs:

Prebaked carbon anodes:	US \$ 55 - 70 per metric ton (net consumption)
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Soderberg paste:	US \$ 40 - 50
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Anode carbon costs depend on many factors, such as types and costs of raw materials used, proportion of carbon recycled as butts in the case of prebaked anodes, etc.

Labour

The labour and staff of an aluminum reduction plant consists of:

Operating labour

Potrooms, carbon plant and casting

Indirect labour

Auxiliary operations, such as power supply, gas cleaning, materials handling, yard gang, watchmen, etc.

Maintenance labour

Mechanical and electrical workshops, cathode rebuilding crew, etc.

Supervision and control

Plant management, laboratory, social services, etc.

The lowest figures for total labour are obtained in highly mechanized large plants in the United States and in France, where figures as low as 11 to 14 manhours per metric ton are reached. In most North American plants this figure is below 20 manhours but in Western Europe and Japan it is usually between 25 and 30 manhours and sometimes even higher in older plants. However, the West European and Japanese aluminum industries are modernizing rapidly and will certainly show a trend towards lower manhour figures in the years to come.

In this connection it should be pointed out that there are two ways of organizing the potroom work. The traditional system is to assign a certain number of cells to one or two workmen who carry out most operations on this limited number of cells. The other method, which lends itself to mechanization and which has been used in North America for considerable time, consists in assigning each operation (such as crust breaking, alumina charging, metal tapping, anode changing or paste charging, etc.) to a crew equipped with specialized equipment; each crew performs their particular operation throughout the entire potroom. This organization of the work has been adopted, at least in part, in the newest reduction plants in Western Europe. The latter method results in considerable labour savings but does not always give as good operating results because no particular workman has the responsibility for the individual cell.

It should also be pointed out that many North American plants and some of the newest plants in Western Europe are situated in industrialized areas and therefore rely to some extent on outside contract work, particularly for maintenance and repairs. A fully self-contained plant therefore requires more labour.

In underdeveloped countries it is not necessary to push the mechanization as far as it is being done now in North America and Western Europe. Besides labour being cheaper in underdeveloped countries, the maintenance of mechanized equipment also presents a problem in reduction plants on account of the highly abrasive nature of alumina, which is present everywhere in such a plant. For new reduction plants in underdeveloped countries it is prudent to figure with 30 to 50 manhours per ton aluminum, depending on plant and cell size, and on location. Labour requirements could be even higher for a small self-contained plant with all auxiliary installations (say less than 10,000 tons per year capacity).

Operating and maintenance supplies

Cathode replacement forms an important part of this cost item. Short cathode life can therefore increase this figure sharply. It takes considerable experience in cathode lining and potroom operation to achieve a long cathode life and it is therefore advisable to figure with a higher figure for this item, at least during the initial years of operation, when planning new reduction plants in underdeveloped countries.

POWER COST

Note that power costs are given here in mills, (one mill = 0.1 US cent).

The availability and cost of power is an extremely important economic factor in aluminum reduction. Power from coal, lignite, natural gas and in particular hydroelectric power developments, is used for aluminum production. Of these power sources, natural gas requires the lowest investment per kilowatt installed, but usually comparatively high fuel cost. Hydroelectric developments, on the other hand, usually require the highest investment but are very cheap to operate. Amortization and interest on capital always form a large proportion of the power cost. The power cost therefore depends to a great extent on write-off time and this is particularly true of hydroelectric power.

The lowest power costs are found in old aluminum plants with fully amortized hydroelectric power plants. In such cases, power costs can be as low as 1 mill and this is probably the case for some plants in Canada and Norway. The highest power cost paid for aluminum production is probably about 6 mills; it is believed that some plants in Western Europe and Japan have power costs of this order, particularly when purchasing power from outside power companies or national grid systems.

The following power cost ranges are believed to be typical for the most important aluminum producing countries:

<u>Country</u>	<u>Mils/KWH</u>
United States	2.0 - 4.0
Canada	1.5 - 3.5
Western Europe	4.0 - 6.0
Norway	1.5 - 2.7
Japan	2.7 - 8.0

The maximum power cost for economic production of aluminum depends of course on the other costs in each case, of which labour is the most important. In North America with its high labour cost the maximum is about 4 mills whereas West European plants can compete with up to 5 or 6 mills power. Aluminum plants in underdeveloped countries have low cost labour but suffer at the same time from other handicaps. The maximum economic power cost must of course be determined in each particular case but the average limit is probably about 4 mills.

CELL SIZE

The advantages to be derived from large units are obvious. When choosing a large cell, the desired production can be attained with fewer units, requiring less operating labour and the production value of each unit justifies a higher degree of mechanization than is possible with smaller units.

The largest cells in commercial operation today are of the following sizes:

North America

Prebake:	85,000 amperes
Soderberg:	130,000 amperes

Europe

Prebake:

Conventional (many small anodes):	90,000 amperes
Continuous (new system with large anode blocks):	128,000 amperes

Soderberg:

In commercial operation:	128,000 amperes
Large scale testing:	150,000 amperes

Experience has shown however that the application of large currents result in considerable operating difficulties primarily due to concentrated heat formation and strong magnetic fields. These effects can be counteracted by reduced insulation and increased ventilation to protect the cell lining from overheating, and by careful design of the busbar arrangement in such a fashion that a uniform magnetic field is created throughout the cross section of the cell.

Cells for 100,000 amperes and above have been adopted for a number of aluminum reduction plants built in the last few years in Europe as well as in the United States, Canada and Japan. The design of these cells is however quite complicated and experienced personnel is required to obtain good results. Somewhat smaller pots are much easier to operate and in underdeveloped countries it may therefore often be preferable to base aluminum projects on a cell size of 50,000 to 80,000 amperes, which is still large enough to be economical with respect to power consumption and maintenance. Cells of this size require of course some additional labour as compared with the 100,000 ampere cells, but this is not believed to be a serious handicap where labour is available at reasonable cost.

In this connection it should be mentioned that it is often advisable to start up a plant at a comparatively low amperage, as large cells in particular are easier to operate with good results at a lower current density. After gaining experience the amperage can be increased with additional rectifier capacity, resulting in a larger and more economical future aluminum production. For example, cells can be designed for initial operation at 65,000 amperes and future increase to 80,000 amperes.

Reduction plant investment decreases with increasing cell size to a certain point. The lowest investment is probably achieved with a cell

size of approximately 70,000 - 80,000 amperes. When the cell size is further increased, investment cost also increases because of larger specific cell size (due to lower current density), greater ventilation requirements and more complex busbar system to counteract the increasingly serious magnetic disturbances.

COMPARISON OF PREBAKE AND SODERBERG SYSTEMS

Both the prebaked carbon and the Soderberg anode systems are widely used today and both have their advantages and disadvantages. The question as to which system to adopt comes up in the early planning stage of any aluminum reduction project as this decision affects all phases of the project. The main points to consider when comparing the systems are therefore discussed below.

Advantages of prebake system

- (1) Lower power consumption, other factors being equal. The main reason for this is the higher conductivity of baked carbon as compared with carbon paste.
- (2) Easier to operate. Particularly with an inexperienced crew it is easier to obtain good operating results with prebake cells.
- (3) The gas is less obnoxious and easier to clean. Consequently, the prebake system is often preferred in cases where air pollution is an important factor.

Advantages of Soderberg system

- (1) Simpler and cheaper carbon plant. In both systems it is necessary to first produce carbon paste and considerable additional baking and rodding facilities are required to produce prebaked carbons from the paste.
- (2) Lower operating labour requirements. The Soderberg system avoids the handling and manufacture of individual anode carbons and is in general more suitable for mechanization.

The two systems are closely competitive with respect to metal quality and carbon consumption, when one takes into account the baking loss when producing prebaked anodes. There is therefore no general answer to the question as to whether the prebake or Soderberg system is the best. This question must be studied carefully in each case.

Plant size has a bearing on the selection of anode system. A minimum plant size of 60,000 - 100,000 tons is required to justify the additional facilities required for a prebake plant. The attached graph shows that the specific investment is lower for Soderberg plants below this capacity, and lower for prebake plants above this capacity. It may still be justified to build a smaller prebake plant if future expansions are planned

or in cases where air pollution restrictions make it advisable regardless of economical considerations.

ALUMINUM FABRICATION

Aluminum is processed into many different metal products and consequently there exist many types of aluminum fabricating plants. The most important fabricating processes have already been described in the section about "aluminum technology", where new fabricating methods of interest to underdeveloped countries have also been described.

CAPITAL COST

Capital cost figures for aluminum fabricating plants are difficult to give in a general report like this in view of the large variety of processes and products. However, an attempt is made to illustrate factors influencing the capital cost of the most important types of fabricating plants.

Rolling mills

Modern continuous hot mills for aluminum sheet cost US \$ 30 to 50 million for hot rolling capacities ranging from 100,000 to 200,000 tons per year in widths up to 100 - 120 inches (2.0 - 2.5 m); these investment figures include cast house and soaking pits for producing and preheating aluminum rolling ingots weighing up to 6 - 10 tons. However, these figures do not include cold rolling, heat treatment and finishing (corrugating, flattening, slitting, embossing, printing, square-cutting, circle-cutting, etc.) facilities. When such facilities are added, full utilization of hot rolling capacities of this magnitude can easily run the cost of the total project into \$ 60 to more than 100 million. However, a proportion of the hot rolled production from a continuous hot mill is usually sold as re-roll stock to other fabricating plants for cold rolling and finishing.

Rolling mills of this kind are not required in underdeveloped countries; the investment, production capacity, maximum width and unit weight of rolling ingot and hot sheet coil are all too high. A conventional arrangement of one or two reversing hot mills and hand fed cold and finishing mills is suitable for productions ranging from 2,000 to 10,000 tons per year. The same hot mill arrangement, but with at least part of the cold rolling being carried out in reel fed mills, is suitable for productions ranging from 5,000 to 30,000 tons per year. Order-of-magnitude investment figures for complete rolling mills of this type, including all auxiliary installations, range from US \$ 1,500 down to US \$ 500 per annual ton of aluminum products, depending on plant size and the variety of finishing equipment included. A 10,000 tons per year plant of this type, capable of producing a maximum finished sheet width of 48 inches (1.2 m), with finishing equipment, would cost US \$ 8 to 12 million.

The new direct sheet casting processes are suitable for productions ranging from 5,000 to 30,000 tons per year. Complete plants of this type, including intermediary rolling and finishing facilities, cost from US \$ 800 down to US \$ 400 per annual ton capacity, depending on plant size and the variety of finishing equipment.

Rod, wire and cable plants

Similarly, the capacity and capital cost of a conventional rod rolling mill are high; rod rolling mills are therefore only justified when a large production (say more than 15,000 tons per year) is being considered. The production of rod, wire and cable can be achieved on a smaller scale at much lower investment by using Properzi machines. This has already been done successfully in several underdeveloped countries.

Extrusion plants

The extrusion processes lend themselves to small operations as extrusion presses, draw benches, straightening benches, etc., can be added gradually. A small extrusion plant (say 2,500 - 5,000 tons per year capacity) can be built for US \$ 1.5 to 3.0 million and later expanded as required. Such a plant would only produce light profiles and tubes; the large extrusion presses required for heavier products would result in a more expensive plant.

Kitchen utensils and hollow ware

Plants for the production of kitchen utensils and other hollow ware from aluminum circles require comparatively low investment. A small plant can be built for US \$ 400,000 - 800,000 and expanded gradually as required by additional deep drawing presses, spinning benches, etc.

OPERATING REQUIREMENTS

Figures for operating requirements cannot be given in a general report such as this, because these requirements vary over a wide range for a large variety of fabricated products.

In general, it can be said that capital charges (amortization and interest) and labour are the most important cost items. Capital charges are very high for modern continuous hot rolling mills, which are highly mechanized and instrumented so that little labour is required. On the other hand, labour requirements are high for lighter rolling mills and for all intermediary and particularly finishing operations. Of course, expensive automatic equipment has been developed also for intermediary and finishing operations and such equipment is economically justified for high production volumes in industrially advanced countries with high labour cost. This is however an area where underdeveloped countries can take advantage of lower labour cost to use cheaper equipment.

In this connection it should be mentioned that aluminum fabricating equipment which has become obsolete in industrialized countries with high labour cost, can still be economical in underdeveloped countries. It is therefore possible for such countries to start an aluminum fabricating industry with a low capital expenditure by purchasing used equipment from industrially advanced countries. Many types of aluminum fabricating equipment, such as rolling mills, extrusion presses, deep drawing presses, etc.,

are usually of very robust construction and can therefore be kept in good condition through many years. Aluminum rolling mills with a considerable proportion of used equipment have been successfully established in several underdeveloped countries in Asia and Latin America.

USE OF FABRICATING FACILITIES FOR OTHER NON-FERROUS METALS

Much of the fabricating equipment used for other non-ferrous metals, such as copper, brass, zinc and nickel alloys, etc., is also suitable for aluminum. This applies for example to rolling mills, extrusion presses, draw benches, etc. On the other hand, aluminum and aluminum alloys require heat treatment temperatures and conditions which differ considerably from those used for other non-ferrous metals; consequently, new furnace equipment is usually required for aluminum.

While it is possible to use for aluminum equipment which has previously been used for other non-ferrous metals, it is on the other hand not advisable to use the same equipment alternatively for aluminum and other non-ferrous metals. The reason for this is that particles of the heavier metals adhering to the equipment (rolls of rolling mills, containers of extrusion presses, etc.) are pressed into the aluminum surface, resulting later in corrosion due to aluminum-heavy metal electrochemical couples. In the case of rolling mills, for example, this can be avoided by changing roll pairs whenever one changes from aluminum to another metal or vice versa; however, this is not usually economical because of the production time lost in roll changing.

VALUE OF FABRICATED ALUMINUM PRODUCTS

The attached table shows the present (December 1962) market value of various semi-fabricated aluminum products in the United States. The difference between the primary aluminum price and the prices for these products illustrates the value of the fabrication in each case.

TRENDS IN USES IN ALUMINUM

PRESENT AND FUTURE USES

The table below shows the most recent distribution figures available for aluminum according to end uses in the United States and Western Europe.

	<u>United States</u> <u>(1961)</u>	<u>Western Europe</u> <u>(1960)</u>
Transportation	22	28
Machinery and equipment	8	10
Electrical	11	13
Building products	25	10
Containers and packaging	7	10
Home and office appliances	12	9
All other	15	20

Everybody agrees that the rapid expansion of aluminum consumption will continue in the years ahead. In industrially advanced countries the greatest increases are expected in transportation (particularly automotive), building products and packaging. In underdeveloped countries the pattern will probably be somewhat different. There the increases are expected to be greatest in the following fields:

Electrical equipment

The electrification of underdeveloped countries will progress at an accelerating pace in the years to come, causing a great demand for aluminum power transmission cables.

Cooking utensils

Cooking utensils and other hollow ware are the first aluminum goods which underdeveloped people will acquire in striving for higher living standards.

Building products

Aluminum building products are particularly attractive in tropical countries because of their durability in climates where other building materials deteriorate rapidly. Aluminum stands up where wood is destroyed by rot and insects, and where galvanized steel rusts.

COMPETING MATERIALS

Aluminum possesses a combination of good properties such as lightness and resistance to corrosion. Aluminum has therefore in course of the last

fifty years replaced traditional materials such as steel, wood and non-ferrous metals for many applications. For anyone who plans to enter the aluminum industry it is important to consider the probable future relationship between aluminum and other competing materials. Due to vast resources of good grade bauxite in many parts of the world and technological advances in the aluminum industry it is reasonable to believe that the cost of aluminum will, in comparison to the general price level, gradually decrease further in the years to come, although not so rapidly as it has decreased during the last fifty years.

Steel

The trend from steel to aluminum will continue in spite of steel costs also decreasing as a result of improving steel technology. The tonnage replaced by aluminum is very important to the aluminum industry although it only forms a marginal proportion of total steel consumption. The main areas for aluminum replacement are for building materials and containers; as to the latter, the coming years may see a considerable shift from tinplate to aluminum.

Copper and zinc

Of the non-ferrous metals, particularly copper and zinc have been greatly replaced by aluminum in recent years. Aluminum has almost completely replaced copper for high voltage power transmission but copper is still almost universally used for other electrical applications. Aluminum is replacing zinc in two major fields: galvanized steel and die-castings. Aluminum will probably continue to take markets away from copper and zinc.

Wood

Wood has already been replaced to a considerable degree by aluminum for house building in North America, particularly where aluminum is used in doors, window frames, weather proof siding, and roofing for farm buildings. Europe is far behind but the trend is also noticeable there and will gain impetus in the years to come. The same trend will also certainly be felt in time in underdeveloped countries, and probably fairly soon in tropical countries where aluminum has particular advantages, as already pointed out.

Plastics

On the other hand, it must be expected that plastics will gain some markets from aluminum. Certain plastics are cheaper than aluminum and are also formed more cheaply into final shapes by injection moulding and other methods. Plastics also have high corrosion resistance. However, the plastics which can compete with aluminum in price lack strength and become brittle with age but aluminum will lose markets to plastics for applications where strength and durability are not important. Some plastics, like Nylon, Teflon and particularly Delrin (all developed by the Dupont company

in the United States) possess strength characteristics comparable to metals but these plastics are still much more expensive than aluminum. However, plastics are made from very cheap and plentiful raw materials (primarily coal, petroleum, natural gas, chlorine and ammonia) and it is therefore possible that cheap and strong plastics will be developed which will prove very competitive with aluminum.

PLANT LOCATION

ALUMINA

The trend now is to build alumina plants close to the bauxite mines. The main reason for this is that 2.0 to 2.5 tons of dried bauxite are required per ton of alumina and it is therefore cheaper to transport the alumina than the bauxite. Furthermore, alumina can be handled rapidly by pneumatic systems. In some cases the expense of drying the bauxite can be avoided.

If the bauxite deposits are located inland the best alumina plant location may be at the closest shipping point on the coast or on a navigable river.

Alumina is imported duty-free into most countries and this gives underdeveloped countries the possibility of creating an alumina industry in connection with their bauxite mines, and shipping the alumina to aluminum producing countries. The United States is an exception and the U.S. duty on alumina has caused U.S. aluminum companies to import bauxite and produce their alumina within the United States.

REDUCTION

Early reduction plants were always built close to cheap hydroelectric power; thus the earliest European aluminum plants were built in Norway and in the Alps, and the earliest North American plants in Niagara Falls and in Tennessee. Since then coal, lignite and natural gas have also become economical power sources and high voltage transmission now permits power to be transferred economically over considerable distances. Today the choice of location is therefore much wider. The present general pattern is as follows:

- (1) In countries with large domestic aluminum markets, such as the United States and Western Europe, reduction plants are now often built inland, close to the centre of gravity of the markets.
- (2) In countries relying primarily on export of their aluminum production, such as Canada and Norway, the tendency is to build new plants on tidewater as close as possible to cheap power sources.

FABRICATION

Availability of labour and low transportation costs to the markets are the main considerations here. Fabricated products must be well packed to avoid damage in transportation and are therefore bulky. Consequently, fabrication plants are usually located in the centres of communications within the markets which they are intended to serve.

ADVANTAGES OF INTEGRATION

Aluminum processing consists of the following four main stages:

Bauxite mining
Alumina
Aluminum reduction
Fabrication

Economic benefits can be reaped from the combination of several of these stages where such an integration is natural. The advantages in lowered overhead and maintenance costs are obvious. Besides these, the following advantages should also be mentioned:

Bauxite mining - alumina combination

Transportation and, in some cases, drying of the bauxite is avoided.

Alumina - reduction plant combination

Cheap power is usually available where there is a reduction plant and caustic soda, used in the alumina process, can therefore be produced economically in such locations. The sodium aluminate solution from the alumina plant can be used to produce synthetic cryolite and recover fluorides from the reduction plant gases.

Reduction plant - fabrication combination

The metal can be transferred from the reduction plant to the fabricating plant in the molten state, thus saving fuel for remelting.

APPROACH TO NEW ALUMINUM PROJECTS

The following is a recommended line of approach for governments of countries in an early stage of industrial development who wish to investigate the feasibility of establishing an aluminum industry in their country. There are of course many ways in which such a project can be investigated and realized, but it is believed that the following illustrates factors which should be considered.

STAGE I - FEASIBILITY STUDY

It is recommended that the first feasibility studies be made by independent consultants. The selection of such consultants depend upon the nature of the project, for example:

- Geological and mining consultants in case of bauxite deposits
- Power consultants in case of aluminum reduction plants
- Metallurgical consultants in case of alumina, aluminum reduction and fabricating plants
- Marketing consultants in case of fabricating plants.

Studies by aluminum producing companies, foreign government agencies, contractors or equipment manufacturers are not so desirable at this stage because of their vested interests (competition with their own metal sales, desire to penetrate the markets of the developing country, wish to obtain engineering or construction contracts or sales of equipment).

STAGE II - PLANT SPECIFICATIONS, ACQUISITION OF DETAILED KNOWHOW AND FINANCING

When the general feasibility has been established, the next step is to have an engineering study made to determine the main specifications for the project. This can be done by engaging an engineering firm co-operating either with a competent metallurgical consultant or a foreign aluminum producing company. Arrangements with an aluminum producing company will greatly simplify the realization of the project but an independent metallurgical consultant can be of considerable assistance in evaluating possible arrangements of this kind.

At the same time, negotiations can be started with foreign aluminum companies to provide detailed knowhow, train key personnel, and, if desired, participate financially in the project.

Usually a detailed engineering study is required to obtain the accurate investment estimates required for financing major projects through foreign loans.

STAGE III - CONSTRUCTION OF PLANT

Based on plant specifications worked out in Stage II, invitations for construction bids can be sent out to qualified constructing firms. These specifications must be accurate and detailed in order to ensure the most advantageous construction contract on truly competitive basis. In this connection it must be remembered that the lowest bid is not necessarily the most advantageous; many factors must be considered when evaluating such bids and it is often worthwhile to retain for this purpose the services of the engineering firm which developed the plant specifications in Stage II.

An engineering firm, or the engineering department of a foreign aluminum production company, should be retained to control the construction work as it progresses and make sure that everything is being built according to specifications.

STAGE IV - START-UP OF PLANT

A smooth start-up will be greatly helped by the assistance of a foreign aluminum producing company, either as participant in the project or on a technical assistance contract basis. The start-up will also be greatly assisted by having key personnel trained in advance in a foreign aluminum plant, as mentioned under Stage II. In any case it would be necessary also to have foreign engineers assist in the start-up, arriving perhaps some months before this takes place and staying on for another six months to one year after start-up. In some cases it may be desirable to engage foreign management and technical personnel for a duration of say two to five years. The necessity for this depends of course on the level of industrial development already reached by the country where the aluminum project is to be established.

TYPICAL ANALYSES OF BAUXITES

Bauxite types:

B = Boehmite (monohydrate)
D = Diaspore (monohydrate)
G = Gibbsite (trihydrate)
C = Corundum (anhydrous)

<u>Location</u>	<u>Type of bauxite</u>	<u>Typical analysis in %</u>				<u>H₂O</u>
		<u>Al₂O₃</u>	<u>SiO₂</u>	<u>TiO₂</u>	<u>Fe₂O₃</u>	
<u>AFRICA</u>						
Ghana						
Yenahin	G	46-51	1	-	17-25	26-29
Mt. Ejuanema	G	57-61	1	1-2	10-12	27-29
Guinea						
Kassa Island	G	54	7	1-2	11-12	28-29
Kindia (Fria)	G	40-42	2-3	-	20-30	25-28
<u>ASIA</u>						
Indonesia						
Bintan	G	54-58	2-4	1	4-10	28-30
India						
Madras, Orissa	G & D	52-58	2-4	6-11	7-14	25-28
Malaya						
Johore	G	55-60	2-7	1	4-6	27-29
<u>AUSTRALIA</u>						
West Australia						
Darling Range	G	48-52	8	4	12-18	27-29
<u>EUROPE</u>						
France						
Bouches-du-Rhone						
Var, Ariege, Herault	B	54-58	1-6	2-3	23-26	10-13
Greece						
Mt. Parnassas	B	57	4	2-3	23	11-13
Others	D & C	58-67	1-2	2-5	15-31	5-12
Hungary						
Bakony	B & G	50-52	5-6	2-3	17-19	17-20
Vertes	B	53-55	7	2-3	20	14
Italy						
Abruzzi, Campania	B	54-58	1-3	3	23-27	11-13

TYPICAL ANALYSES OF BAUXITES (continued)

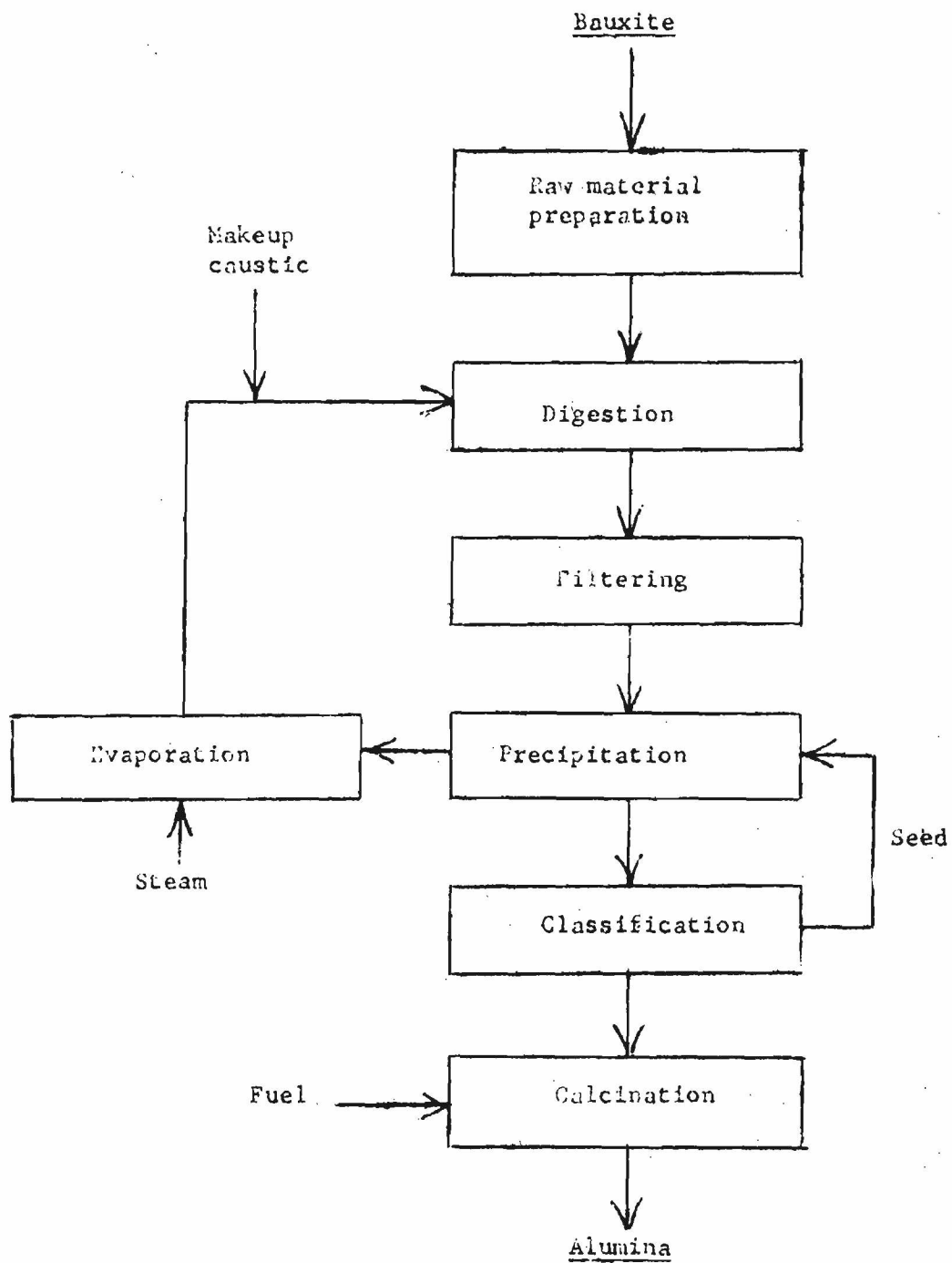
<u>Location</u>	<u>Type of bauxite</u>	<u>Typical analysis in %</u>				
		<u>Al₂O₃</u>	<u>SiO₂</u>	<u>TiO₂</u>	<u>Fe₂O₃</u>	<u>H₂O</u>
<u>EUROPE (continued)</u>						
Rumania Bihar	D	57	2-4	3	24	12
Soviet Union Northern Ural	D	49-59	3-7	2	21-24	11
Yugoslavia Istria	B	54-59	2-5	3-4	20-24	12-15
Drnis	B & G	51-53	1-3	2-4	20-23	20-22
Mostar	B	56-62	1-4	3-4	20-25	12-15
<u>NORTH AMERICA</u>						
United States Arkansas	G	52-58	6-10	2-3	6-14	28-30
Jamaica	G & B	50-53	1-3	2-3	17-20	26-27
Haiti	G	47	3	?	22	?
Dominican Republic	G	46-49	1-5	?	19-21	?
<u>SOUTH AMERICA</u>						
British Guiana	G	50-61	2-9	1-2	3-10	26-32
Surinam	G	57-59	2-4	1-3	5-6	31-32
Brazil Pocos de Caldas	G	54-58	3-7	1-2	6-10	28-29

VALUE OF FABRICATED ALUMINUM PRODUCTS

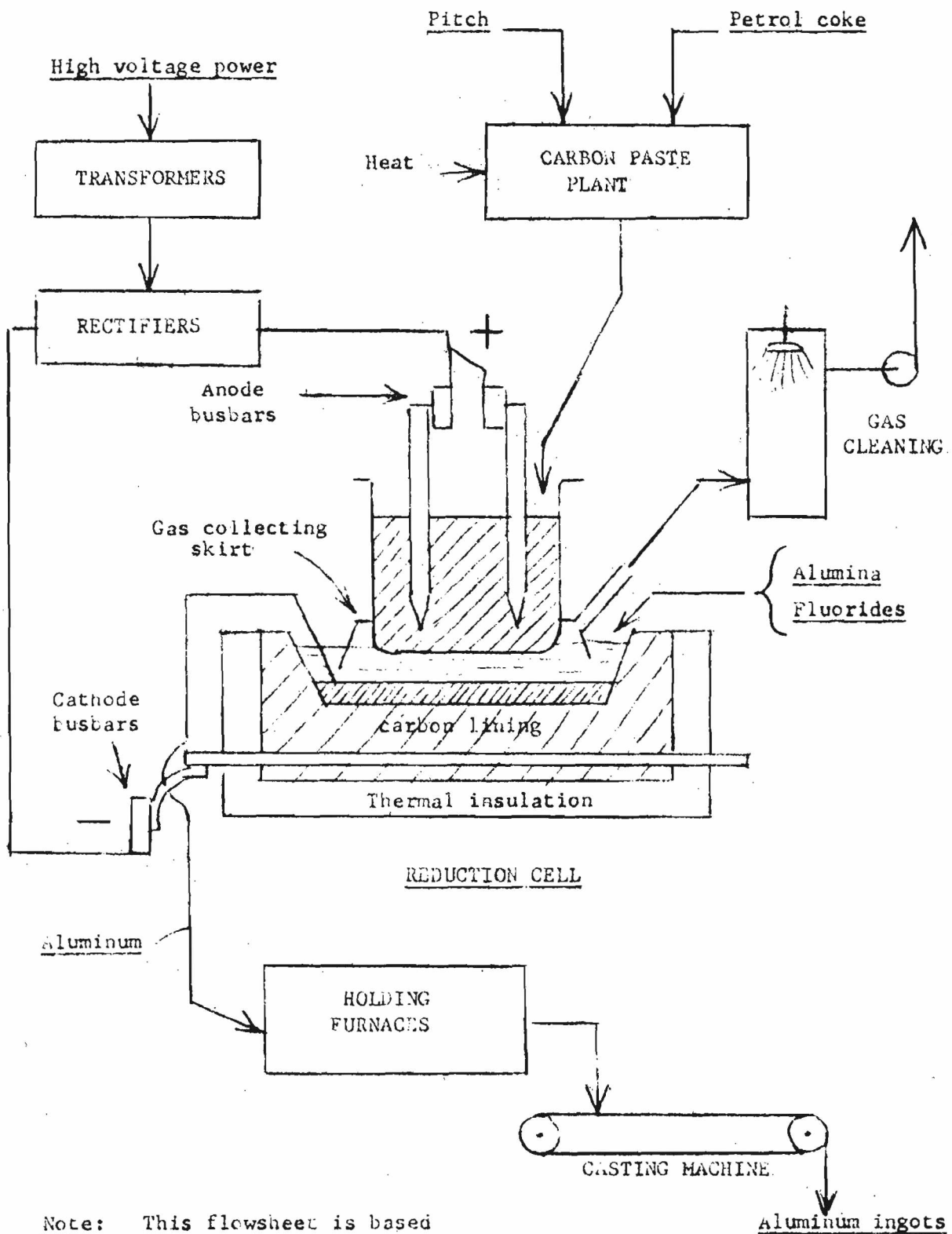
(USA quotations, December 1962)

	<u>US c/lb</u>	<u>US \$/metric ton</u>
<u>Primary aluminum price</u>		
Unalloyed ingot	22.5	496
<u>Sheet</u>		
Pure aluminum and common alloys, 0.025" (0.64 mm) thickness:		
coiled	37.0 - 42.3	815 - 933
cut to length	43.9 - 46.4	967 - 1022
Building sheet, 0.050" (1.27 mm) thickness:		
coiled	35.5	782
cut to length	39.5	870
<u>Circles</u>		
from coiled stock, 0.025" (0.64 mm), 12" (30 cm) diameter and over:	47.0	1036
<u>Foil</u>		
0.0035" (0.09 mm)	56.1	1236
0.00035" (0.009 mm)	75.6	1666
<u>Plate</u>		
Strong alloy, $\frac{1}{4}$ - $\frac{3}{4}$ " (6.4 - 19 mm) thickness, cut to length	59.5	1289
<u>Extrusions</u>		
Factor 18-20, weight per foot: 0.5 - 1.5 lbs (3.6 - 11.0 kg/m):		
Solid profiles	40.5 - 61.2	893 - 1348
Hollow profiles	50.5 - 88.5	1113 - 1950
<u>Electrical conductor</u>		
ACSR (aluminum cable with steel core)	33.5	782
All aluminum cable	40.3	888
Conductor alloy cable	44.4	978
<u>Wire and rod</u>		
Coiled 3/8" (9.5 mm) redraw rod:		
Pure aluminum	28.0	617
Conductor alloy	31.2	688
Screw machine stock rod:	59.2 - 66.2	1305 - 1460

BAYER ALUMINA PROCESS FLOWSHEET

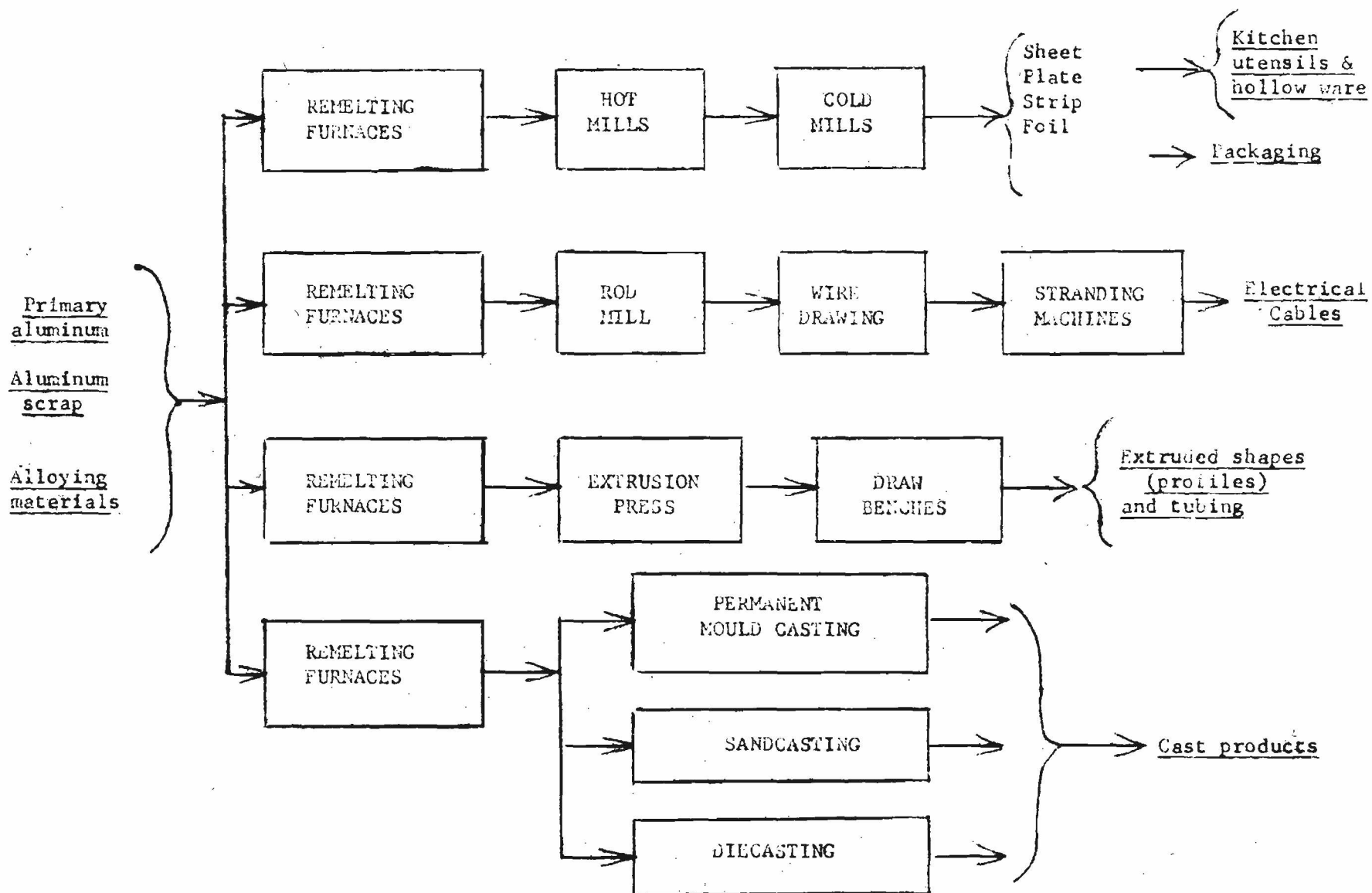


ELECTROLYTIC ALUMINUM REDUCTION PROCESS



Note: This flowsheet is based on the Soderberg system.

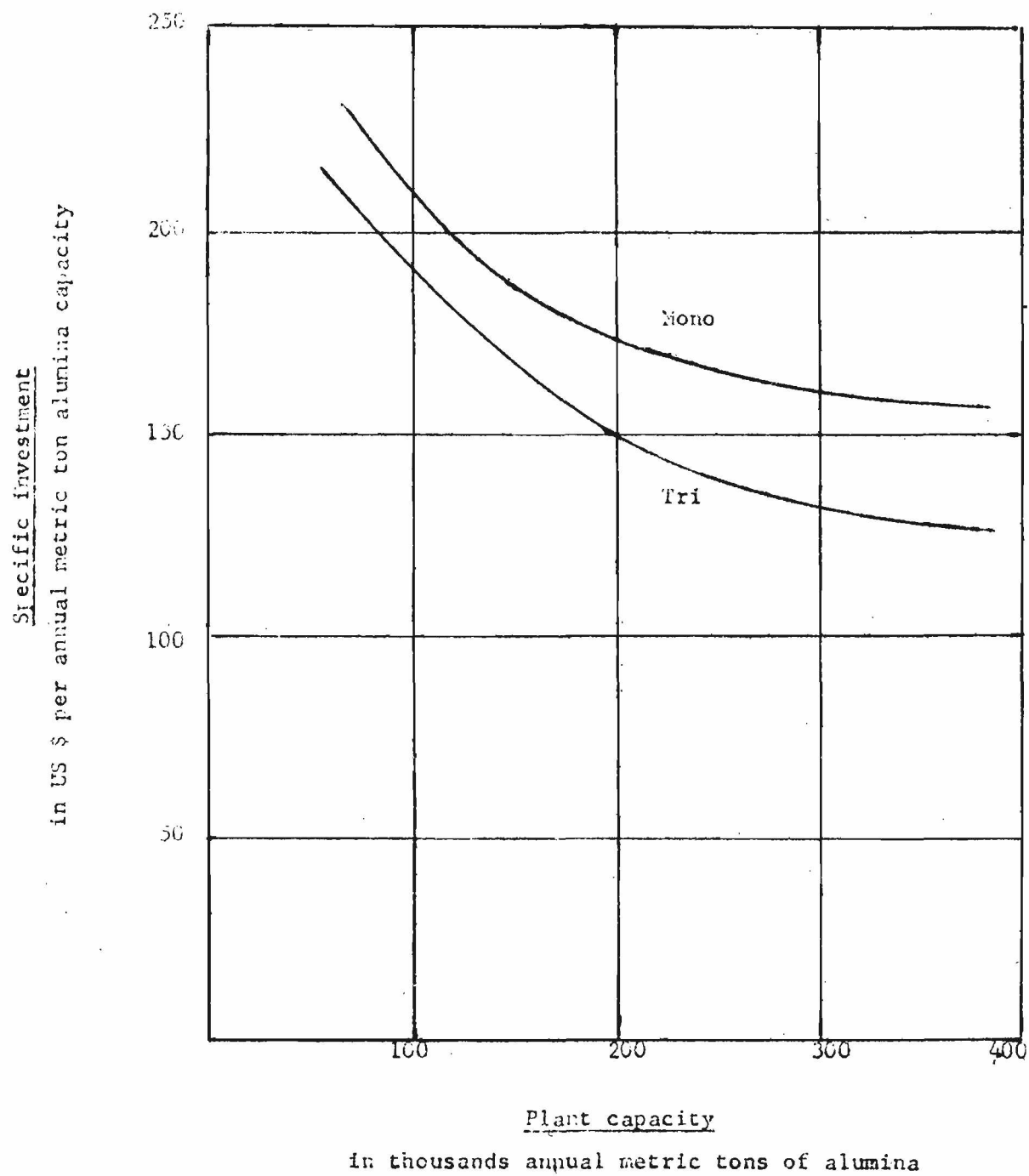
ALUMINUM FABRICATION - GENERAL FLOWSHEET



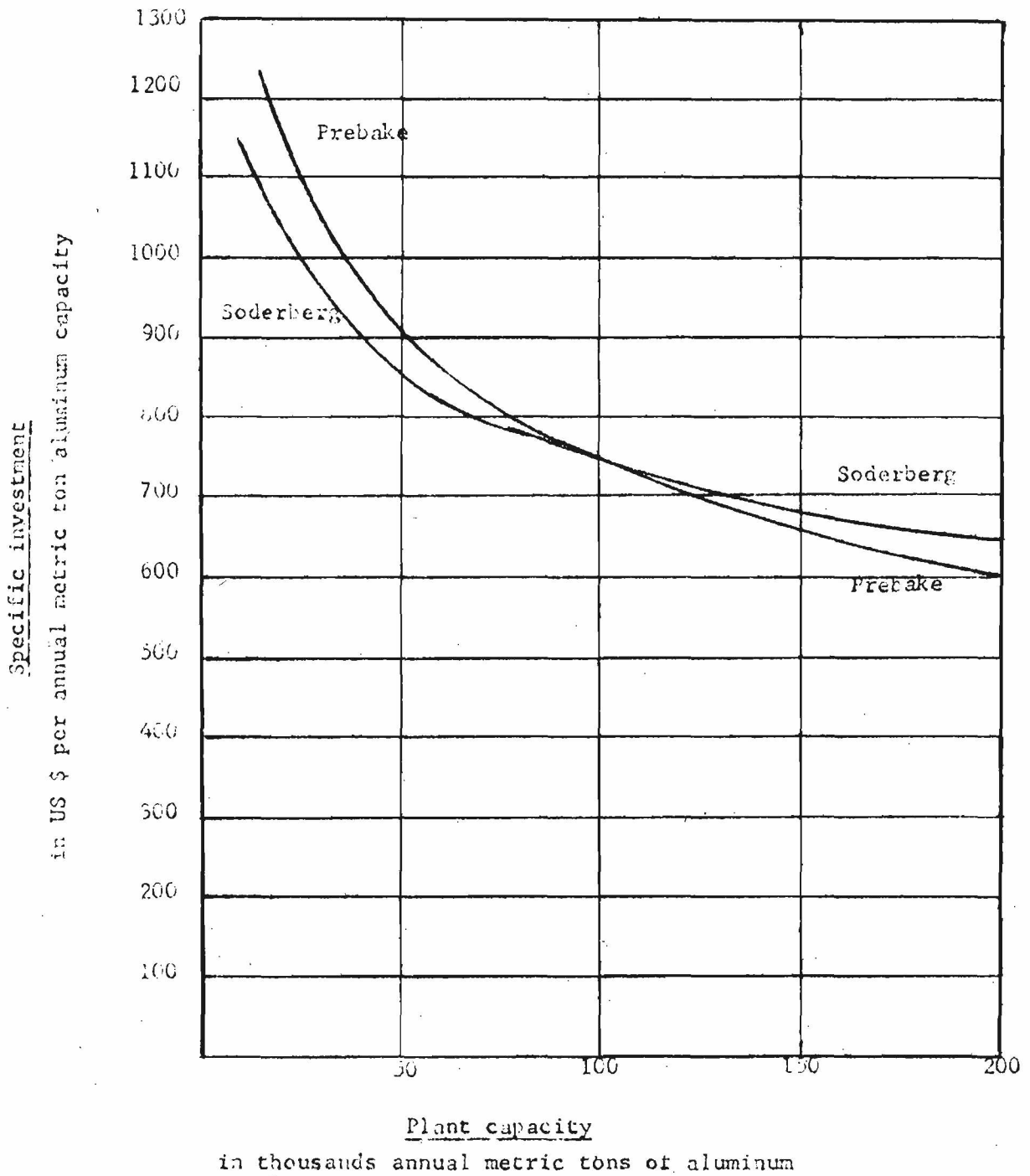
CAPITAL COST

BAYER PROCESS ALUMINA PLANTS

for mono- and trihydrate bauxites



CAPITAL COST
ALUMINUM REDUCTION PLANTS
Prebake and Soderberg anode systems



ERRATA

Page 20

Instead of:

(from 30 to 120 kg per metric ton of alumina)

please read:

(from 30 to 150 kg NaOH per metric ton of alumina)

Page 21

The monohydrate bauxite on which the shown operating requirements are based, has actually the following composition:

Al_2O_3	53%
SiO_2	7%
Fe_2O_3	25%
TiO_2	3%
H_2O	12%

Page 24

About the middle of the page one should read:
(500 to 1,000 tons Al_2O_3 per day)

Page 31

About the middle of the page is shown the cost of Soderberg paste.
This should read:

U.S. \$40 - 50 per metric ton of paste

